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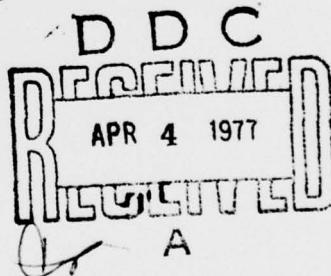


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CRYOPEDOLOGICAL RESEARCH IN THE CONSTRUCTION OF DAMS UNDER SEVERE CLIMATIC CONDITIONS

N.A. Tsytovich and Ya.A. Kronik



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The task of mastering our country's Far North and Northeast, one posed by the Communist Party of the Soviet Union and the Soviet government in recent years, means that there must be a substantial increase in hydraulic engineering construction in these regions. Undertaking hydraulic engineering construction in the regions of the Far North in turn means finding solutions to a whole host of problems, among which problems of engineering cryopedology (permafrost study), as they apply to hydraulic engineering construction, or to problems of hydraulic engineering cryopedology, have an important place. Until recently, virtually no research had been conducted in these problems, because all earlier research had been conducted for purposes of road and airfield construction, and for building foundations.

Soviet scientists and hydraulic engineers have given priority to questions concerned with the need to take into consideration cryopedological peculiarities in hydraulic engineering construction in the Far North. Some of the general considerations of cryopedological peculiarities of hydraulic engineering construction in areas where the permafrost is widespread were presented in the first works devoted to problems of hydraulic engineering in the north (Ye. V. Bliznyak, 1937; P. A. Bogoslovskiy, 1957, 1963; A. V. Stotsenko, 1959, 1963; V. A. Sereda, 1959; G. A. Borisov and G. Ya. Shamshura, 1959, and others). However, these works, which reviewed what were primarily questions concerned with the thermal regime, and with first experience in the construction of small dams on frozen bases, had not given the necessary attention to study of the cryogenic processes that take place in dams, in their bases, and in the sides of the reservoirs. Nor did they raise questions of the need for complex cryopedological research.

This article will review some of the initial results of complex cryopedological research based on the physicochemistry, physics, and mechanics of frozen soils, conducted by the Mechanics of Soils, Bases, and Foundations Section of the Department of Hydraulic Engineering at the V. V. Kuybyshev Moscow Construction Engineering Institute (Head -

Corresponding Member of the Academy of Sciences of the USSR, Doctor of Technical Sciences, Professor N. A. Tsytovich), in 1964.¹

This research included study of the problem of frost heave of soils, as applicable to hydraulic engineering practice, and the development of the corresponding antiheave measures, of questions concerned with heat and moisture transfer and temperature deformations, of the study of the processes involved in structure formation in frozen and thawing soils, development of methods for conducting field and laboratory cryopedological research and design of the corresponding instruments and meters, the development of frost danger (heaveability) and frost resistance of soils used in hydraulic engineering construction and the procedures to use to find these values, full-scale observations of temperature regimes and dam behavior, and the development of the thermal and physical bases for the preparation, storage, and winter placement of cohesive soils in qualitative hydraulic engineering embankments.

Tasks related to rational engineering methods for controlling the physical and physicochemical phenomena and processes are being solved by using behavior patterns research has discovered in cryopedological processes, effective methods of strengthening and anchoring frozen and thawing rocks are under development, and the technology of winter hydraulic engineering earth work is being perfected. All of these questions are being studied in connection with the construction of the Vilyuysk and Ust' Khantayka hydroelectric stations.² Research is planned in connection with the planning and construction of the Kolyma Hydroelectric Station.

1. The section has been studying special aspects of this problem since 1956. The research has, for example, included that by S. B. Ukhov in the artificial salinization of soils to deal with freezability and ensure the erection of embankments in the wintertime, by N. V. Ukhova in the development of methods for forecasting the temperature resistance of frozen dams made of local materials, and by Ya. A. Kronik in the antiheave salinization of soils of hydraulic engineering structures. But this section did not embark on complex cryopedological research until recently.

2. See the reports of the research by the Moscow Construction Engineering Institute conducted in the Physics and Mechanics of Frozen Soils Laboratory (responsible researcher Ya. A. Kronik) titled "Research in Changes in the Physical and Mechanical Properties of Artificially Salinized Soils of the Screen of the Rock-Filled Dam of the Vilyuysk Hydroelectric Station," Vols. I, II, 1966-1967; "Recommendations for the Experimental Salinization of Soils of the Upper Part of the Screen for the Dam of the Vilyuysk Hydroelectric Station to Protect Against Frost Heave," 1967; "Research in the Frost Heave of Soils of the Screen of the Dam for the Vilyuysk Hydroelectric Station," Vols. I, II, 1967-1968; "Recommendations for the Winter Placement of Cohesive Soil in the Core of the Ust'-Khantayka Dam," 1969; "Thermal and Physical Research in the Preparation and Winter Storage of Cohesive Soils for the Core of the Ust'Khantayka Dam," Vol. I, 1969; "Research in the Danger of the Freezing of Khantayka Soils," Vols. I, II, 1968-1969.

Experience in the construction of the first high dams in the Far North (Vilyuysk and Ust'-Khantayka) revealed that the most pressing problem was that of cryogenic (frost) heave, and the danger of freezing of the cohesive soils used for the antifilter elements of dams made of local building materials.

Accordingly, some results of the research conducted at the V. V. Kuybyshev Moscow Construction Engineering Institute bearing on this problem follow.

STATEMENT OF THE PROBLEM OF CRYOGENIC HEAVE OF SOILS IN HYDRAULIC ENGINEERING CONSTRUCTION

Heaving of soils as they freeze is the principal cause of dangerous deformations and destruction of foundations of buildings, light structures, road and rail beds, airfield coverings, irrigation hydraulic engineering structures, and various kinds of dams built of local materials, etc. The problem of frost heave was not generally considered in connection with hydraulic engineering structures, at least not until recently. Research in this problem was begun in 1964, in the Frozen Soils Laboratory of the Department of Mechanics of Soils, Bases, and Foundations at the Moscow Construction Engineering Institute.³

The principal danger from frost heave of soils for various structures reduces to the fact that under definite temperature-humidity conditions in soils with the capacity to heave there develop significant deformations of the surface layers during periodic seasonal freezing, and these deformations can cause substantial deformation to take place in structures and elements of dams built of local materials, and this, in time, will result in their destruction. Moreover, because of deformation of the surface, and the development of moisture migration processes, the upper zone of the freezing soil becomes unconsolidated and water-logged. This leads to a drastic reduction in the strength and filtering properties of soils during thawing, so that in no case is this zone acceptable for use in vital hydraulic engineering earthen structures.

We conditionally understand that soil deformation attributable to frost heave means deformation of the surface of the soil, with increase in volume during freezing, followed by settling during thawing.

3. The research was conducted at the request of the ROSGIPROVODKHOZ [Republic State Institute for the Planning of Water Management and Reclamation Construction of the State Committee of the Council of Ministers for Water Management of the RSFSR] Planning Institute, with the participation of Ya. A. Kronik and Z. S. Artyushkin, under the overall supervision of N. A. Tsytovich.

Research in the field of soil frost heave as applicable to hydraulic engineering practice can be broken down into:

1. soil heave during freezing in the course of winter placement in earthen structures, and in the earthen antifilter elements of dams;
2. heave of the upper zone of earthen dams and antifilter elements of rock and earth-fill dams during alternating freezing and thawing during the period the structure is in use;
3. heave of the slopes of earthen hydraulic engineering structures;
4. heave of the soils of the bases of hydraulic engineering structures.

Heave of soils during winter placement. It is extremely difficult, and given the conditions that prevail in the Far North, practically impossible, to avoid freezing of soil during the removal of the thawed layer, consolidating it to standard density, and covering with the next thawed layer in the course of winter placement of soils. Some freezing of the upper zone of the layer of soil being placed occurs during this period, even when removal is highly intensive.

Frost heave will begin during the winter placement of cohesive soils as they freeze. This is the result of the onset of the process of freezing and subsequent growth of ice lenses because of the migrating moisture. Cryogenic heave during one-dimensional freezing leads to the upper part of the layer being placed becoming water-logged because of the migration of moisture to the freezing front from the lower part of the layer, or from the underlying thawed layer previously placed in the structure. Moreover, more intensively developing heave of the upper part of the layer leads to considerable unconsolidation of that layer, and this has in fact been observed. These two factors cause a reduction in the strength and filter characteristics in the upper part of the layer and can, during thawing, lead to the appearance in the earthen element of the dam of unconsolidated, water-logged interlayers and to the occurrence of concentrated filtration flows along them. This occurred during field tests during the construction of the Vilyuysk dam (the tests were conducted by the Vilyuysk Hydroelectric Station Construction Trust jointly with the B. Ye. Vedeneyev All-Union Scientific Research Institute of Hydraulic Engineering). All of this will result in change in the static and filter stability of the antifilter elements, as well as of the structure as a whole, and this, naturally, is unacceptable.

Some freezing of an applied layer from below is possible during the winter placement of cohesive thawed soils on a base that has been deeply frozen for a long time (when ambient temperatures are between -40 and -50°C), and this too can have undesirable consequences. But it should be noted that it is extremely difficult to prevent soil from freezing from below.

The frost heave of soils, as described above, requires that the processes involved be taken into consideration in the planning and construction of hydraulic engineering structures, and in the development of the corresponding antiheave measures.

Heave of the upper zone of earthen dams and of antifilter elements. This case is even more dangerous, and for the following reasons. Most of the antifilter element (screen core), or of the earthen dam, is in a thawed water-saturated condition (if the dam was built in accordance with the "thawed" variant) during the period of use. The upper zone of the earthen element of the dam, which is subject to seasonal freezing and thawing, will be under optimum conditions for the development of an open system frost heave. This can be explained by the fact that during the summer the dam's normal upstream water level (NUL) is a maximum, and the soil of the upper part of the dam's screen (core) is completely saturated with water; up to the NUL mark because of filtration, and above it because of capillary rise and atmospheric precipitation during the fall of the year. With the onset of winter, and as a result of decrease of storage, which coincide in time, these soils begin to freeze and there is a steady seepage of moisture to the freezing front from the thawed layers below the depression curve.

Thus, the soils of the upper zone of the screen, core, or earthen dam above the level of decrease in storage will be subjected to alternating seasonal freezing and thawing, and their heave will be of the open system type, which can lead to significant deformations of the heave. This latter will cause destruction of the crest of the dam, as well as of the road cover atop it, and can, in time, as should be obvious, affect the filter and static stability of the upper zone of the dam as a whole. It will be difficult to maintain the normal upstream water level if there is a substantial reduction in the antifilter stability of the dam's upper zone. Moreover, it is possible, in the case of an above-normal upstream water level, for water to overflow through the upper zone of the dam's screen (core), as was the case at the Myaundzha dam during the 1962 floods [3], where, despite the dam's having been built according to the frozen variant, the body of the dam showed significant development of freezing (cryogenic) processes.

Accordingly, the development of frost heave of the upper zone of a dam is something that cannot be accepted in the practice of hydraulic engineering in the north.

Heave of the slopes of earthen hydraulic engineering structures. Seasonal temperature variations cause the development on the slopes of dams and earthen dams built according to the "frozen" variant, of an active, or seasonally thawing, layer, the thickness of which can be 2 to 3 meters in places, even in the case of small dams of the Myaundzha type [3]. The formation of an active, seasonally freezing layer that is even thicker can be anticipated in the case of large dams built according to the "thawed" variant.

Frost heave deformation of the slopes of various types of dams during repeated freezing and thawing when the dams are in use will, inevitably, result in the development of solifluction processes, and the destruction of the slopes. The lower slope will be in the greatest danger, but local collapses of the upper slope in the zone of the variable level are possible. M. M. Grishin [6], P. A. Bogoslovskiy [2], and G. B. Yappu [19], have also pointed out the need to take this danger into consideration in the planning and construction of earthen dams. Heaving of slopes is even more dangerous for canals in drainage and irrigation systems.

Heave of the soils of the bases of hydraulic engineering structures. Cryogenic heave of soils of bases is dangerous for hydraulic engineering structures of irrigation and drainage systems (canals, races, chutes, and the like), as well as for certain other hydraulic engineering structures, the bases of which are soils subject to heaving (water conduits and spillways, buildings and structures built around dams, and others, for example). In this case heave during seasonal freezing and thawing will create the same difficulties as those generally encountered when building foundations and roads. However, in the majority of cases deformations attributable to heaving will be much greater than is the case when building foundations. The reasons are these. Small hydraulic engineering structures are much lighter in weight than buildings, for which an increase in weight reduces the pressure and deformation caused by frost heave. Second, the fact that all water-conducting hydraulic engineering structures (particularly those in drainage and irrigation systems) have a zone of water-logged soil in their bases, because of filtration of water, thus leading to the development of substantial deformations attributable to heave when the bases freeze, must not be overlooked.

Particular attention must be devoted to the spillway canals of dams built in the Far North. Spillways tend to thaw the ground around them when dams are built in accordance with the "frozen" variant, and this leads to the appearance of some sort of a zone of a seasonally active layer during the first stage of the development of the thawing zone. Frost heave that develops when this layer freezes causes some deformation of the spillway canal, which, initially at least, is possible and relatively small, but this, in turn, unavoidably increases the filtering of the water out of the canal at the base, significantly accelerating thawing, and in time this will result in destruction. The main cause of the destruction of spillways in such cases of course is the thawing of the base, but it should be obvious that frost heave deformation is interrelated with other cryogenic phenomena that aid in the development of this process. Failure to take this phenomenon into consideration in planning already has resulted in the destruction of many irrigation installations in the Far East [Type Projects of ROSGIPROVODKHOZ,* 1963; Report of the Moscow Construction Engineering Institute, 1964-1965].

*See footnote 3 for expansion.

Development of more or less extensive frost heave deformation is characteristic of all soils where danger of freezing exists. Criteria for such soils are all too conditional at the present time and those that do exist were developed as applicable to the practice of foundation building, and to road and airfield construction. There still are no criteria for such soils that are suitable for use in hydraulic engineering construction in the Far North. The essentiality and the special importance of this question to dam building in the north must be emphasized. Instructions as to the unsuitability of heaveable soils for building dams have appeared recently in a number of cases, but what is not clear to the hydraulic engineers, to the planners and builders, is what is meant by the term "heaveable soils."

Research in this extremely important question is in progress in the Department of Mechanics of Soils, Bases, and Foundations at the Moscow Construction Engineering Institute.⁴

FROST DANGER (HEAVEABILITY) CRITERIA FOR SOILS USED IN BUILDING DAMS IN THE FAR NORTH

The frost danger in cohesive soils is understood to mean the tendency of such soils to some degree of frost heave during freezing.

The main criteria for frost danger attributable to soils used at the present time to build foundations are grain composition, freezing conditions, and humidity prior to the onset of freezing (Construction Norms 91-60,⁵ Instructions 1963, and others). Experience in the construction of the Vilyuysk and Ust'-Khantayka dams, the first of the big northern dams in our country, revealed that cohesive soils with a high content of coarse detritus generally widespread in the regions of the Far North, can be used as the antifilter elements. In accordance with the standards (Construction Norms 91-60, Instructions 1963, and others), coarse detritus with a content, in the form of a filler, of particles less than 0.1 mm in size, and in an amount in excess of 30% by weight, that can freeze under moisture conditions, is included among the heaveable soils. Analysis of the data on the grain composition of Vilyuysk soils revealed that specifications (1964) permitted the placement in the screen for the Vilyuysk dam of rock and land waste loams with a content of particles measuring less than 0.1 mm of from 17% to 37%, whereas in fact, according to the data, this magnitude was between 40% and 41%, and between 49% and 55% for soils from borrow pit No. 10. And the Khantayka soils recommended for use in the core

4. See the report on research at the Moscow Construction Engineering Institute titled "Research in the Danger Presented by the Freezing Khantayka Soils."

5. Note that the new norms, SNIP-P-B, 6-66, issued as the replacement for 91-60, do not include this question.

6. See the previously cited reports on Moscow Construction Engineering Institute research.

of the Ust'-Khantayka dam had indices very close to those cited. Accordingly, soils acceptable for placement in the anti-filter elements of dams in the Far North contain over 30% particles measuring less than 0.1 mm, and are heaveable soils in terms of grain composition.

The particular frost danger criterion is very conditional. Road construction practice in the United States, at least in the majority of the states, has adopted lower values (maximum 10%) for permissible content of silty clay particles. Laboratory and full-scale research at the Moscow Construction Engineering Institute have developed the fact that Khantayka and Vilyuysk soils used in the construction of antifilter elements of dams, can be practically nonheaveable, given constant grain composition but variable freezing conditions and various initial humidity-density conditions prior to freezing, that is, deformation attributable to frost heaving does not appear. But these soils can heave badly when frost heaving is very intense and is accompanied by excess ice outflow and considerable unconsolidation of the soil. The values for the heave coefficients can be as high as 25% to 49%. Figure 1 presents the heave coefficient, C_h as a function of the initial compactness of Vilyuysk loam, γ_1 , with a constant initial moisture $W_0 = W_{opt}$.

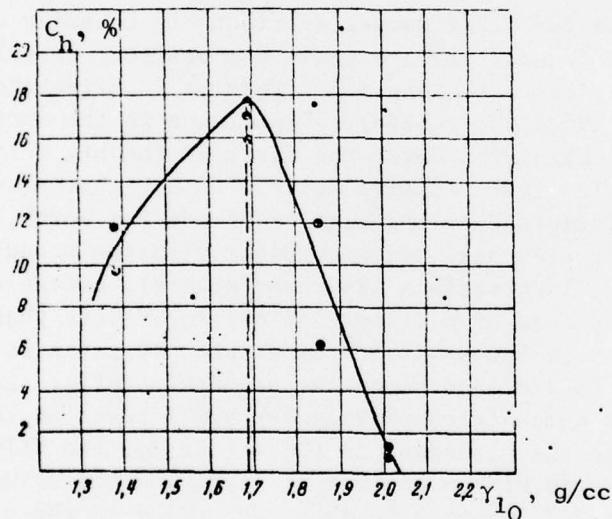


Figure 1. Heave coefficient, C_h as a function of the initial compactness of Vilyuysk loams, γ_1 , with moisture W_{opt} .

These factual data indicate quite clearly the conditionality of the frost danger criterion adopted in foundation building, so it cannot be recommended for use in dam building without additional, special, research, which must be undertaken in the near future. However, carefully approaching

a quantitative evaluation of the frost danger criterion in terms of grain composition, as well as prior to elucidation in future research of the acceptable content of silty clay particles in soils used in northern dam building, what must be done first of all is to hold to the tendency, verified in the practice of permafrost study, toward a reduction in the content of silty clay particles in the soil mixture, and not permit a content of these particles (less than 0.1 mm) above a predetermined magnitude, refining this latter from the results of special research in frost danger for specific soils.⁷

Soils can be broken down into slightly, average, and extremely heaveable, in terms of degree of heaveability, depending on moisture, depth, and freezing conditions. Because the majority of the researchers are of the opinion that soils with a prefreezing moisture content $W_0 \leq W$ are slightly heaveable, in the practice of building the first large northern dams it also was acceptable to place in antifilter elements soils with an initial moisture not exceeding the values of the rolling limit for silt (a moisture content of $W \leq 20\%$ was permissible for Vilyuysk rock and land waste loams, and $W \leq 16\%$ to 20% for the Khantayka).

However, research at the Moscow Construction Engineering Institute established the fact that existing procedures for determining the moisture content and the compactness of coarse detrital soils and their components, silt and coarse detrital fractions, resulted in substantial errors, so were not appropriate for use in dam building. This led to the development of a new procedure for determining the moisture content and the compactness of soil mixtures, one that made it possible to significantly refine the frost danger criteria in terms of moisture content (Kronik, 1967, 1968). In the case of the Vilyuysk rock and land waste loams (borrow pit No. 11), for example, the recommendation was not to accept soils for winter placement with a moisture content greater than 14% (when the content of coarse detrital fractions was $p = 0.5$), and in the case of the Khantayka pebbly and gravel loams with a moisture content greater than 10% to 12% (when $p = 0.5 - 0.3$, respectively).

But even these moisture content criteria are somewhat conditional because, as experiments have demonstrated, the Vilyuysk and Khantayka soils showed perceptible frost heave deformations ($C_h > 4\%$), under optimum open system heave conditions [when $\gamma_1 = (0.91 - 0.93) \gamma_{1 \text{ opt}}$].⁸ Accordingly, at the present time frost danger research at the Moscow Construction Engineering Institute is proceeding along the following lines:

7. Research of this nature will be conducted by the Moscow Construction Engineering Institute, for example, for the Ust'-Khantayka Hydroelectric Station construction management.

8. See the reports of Moscow Construction Engineering Institute research, previously cited.

(1) establish the limit deformations attributable to frost heave of soils that would be dangerous for earthen elements of hydraulic engineering structures, and use them as the basis for the development of frost danger (heaveability) criteria for soils acceptable for placement in a dam, as well as the methodology for determination of those criteria;

(2) research in changes in the physicomechanical and filter properties of soils under the effects of cryogenic processes and use the results as the basis for the development of frost danger criteria for soils. At the same time, frost resistance is understood to mean the capacity of soils to retain their construction properties (primarily strength and filter properties, as those important to hydraulic engineers) over a great many freezing and thawing cycles.

The heave coefficient, C_h , equal to the ratio of the heave deformation increment, Δh_h , during freezing to the depth of freezing of the ground, ξ , with the condition of the ground prior to freezing and freezing conditions taken into consideration, is recommended as the most general criterion of freeze danger for soils.

The methodology developed by the Moscow Construction Engineering Institute is recommended for use in determining the heave coefficient.⁹ The following breakdown of soils, in terms of frost danger, and based on the results of laboratory and full-scale research in the frost danger presented by Vilyuysk soils, can be recommended as a first approximation:

when $C_h < 2\%$ practically nonheaveable soils;
 $C_h = 2 - 5\%$ slightly heaveable soils;
 $C_h = 5 - 10\%$ average heaveable soils;
 $C_h > 10\%$ extremely heaveable soils.

Given the proposed frost danger criteria, extremely heaveable soils are not recommended for use in building dams in the Far North. They could be used as a last resort, but even then only after special studies had been made, antiheave measures had been developed, and further, only after the corresponding engineering and cost factors had been justified.

Practically nonheaveable soils can be recommended for placement in a dam, even in the wintertime, without the need for any antiheave measures.

Slightly, and average, heaveable soils are suitable for use in building dams when antiheave salinization of contact zones is used during winter placement, a procedure that was adequately checked and developed during the building of the screen for the dam for the Vilyuysk Hydroelectric Station.

9. See the Moscow Construction Engineering Institute research report, "Research in the Frost Danger of Khantayka soils."

The criterional values considered for the heave coefficients show that the maximum permissible deformation attributable to frost heave of soils used in building dams is $C_h = 2\%$. Laboratory experiments, and full-scale observations, made by the Moscow Construction Engineering Institute during the winter building of the screen for the dam for the Vilyuysk Hydroelectric Station revealed that at these heave values tightly compacted soils showed no significant unconsolidation, nor was any loss of strength, or reduction in antifilter stability, observed after thawing. We should point out that the maximum permissible deformation attributable to heaving of the ground in the case of foundation building is considered to be $C_h = 1\%$, and in the case of vehicular highway construction $C_h = 1.1$ to 3.7% (depending on how well the road is built).

Research conducted at the Moscow Construction Engineering Institute also established the fact that the normal heave pressure during the open system freezing of Vilyuysk soils was 2 kg/cm^2 , and somewhat higher. However, a pressure on the soil of 2.5 to 3 kg/cm^2 practically suppressed frost heave. It therefore can be assumed that the layers of soil placed in antifilter elements lower than 12-15 meters from the crest of the dam, where the pressure of the overburden exceeds 2.5 to 3 kg/cm^2 , will not experience the destructive action of frost heave if these layers are subjected to freezing under predetermined conditions. This conclusion is highly important, because it is not, at this time, entirely clear whether or not the antifilter elements of rock-filled dams built in accordance with the "thawed" variant will partially freeze. There already are data available that show that in the wintertime some freezing of part of the screen, or core, is possible on the side of the lower knife edge of the talus.

Figure 2 contains data on temperature distribution over the height of the screen for the Vilyuysk Hydroelectric Station, obtained after observation drilling in the summer of 1968, by VILYUYGESSTROY [Vilyuysk Hydroelectric Station Construction Trust] and the Vilyuysk Permafrost Scientific Research Station of the Siberian Division of the Academy of Sciences of the USSR. These data show that in the main the entire screen is in the thawed state, but that there is a small zone (about 10 meters) below freezing ($t_s = -1.6^\circ\text{C}$). However, final conclusions must remain for the conclusion of a longer period of full-scale observations of the temperature regime at the screen of the Vilyuysk dam, and at the core of the Ust'-Khantayka dam.

It is difficult at this time, even on the basis of data on loads that can suppress heaving (2.5 to 3 kg/cm^2 for the Vilyuysk rock and land waste loams), to arrive at a conclusion as to the safety and acceptability of the freezing and thawing of the middle and lower, that is, the loaded, parts of the screen (core), because the problem of the development of cryogenic phenomena and processes within the strata of the ground, as well as in dams, has not been adequately researched. Permafrost study contains numerous examples of the occurrence of thick strata of ice, of ice bands, lenses, and unbroken veins of ice at depths much deeper than 10 to 15 meters, the formation of which today still remains to be completely and finally explained.

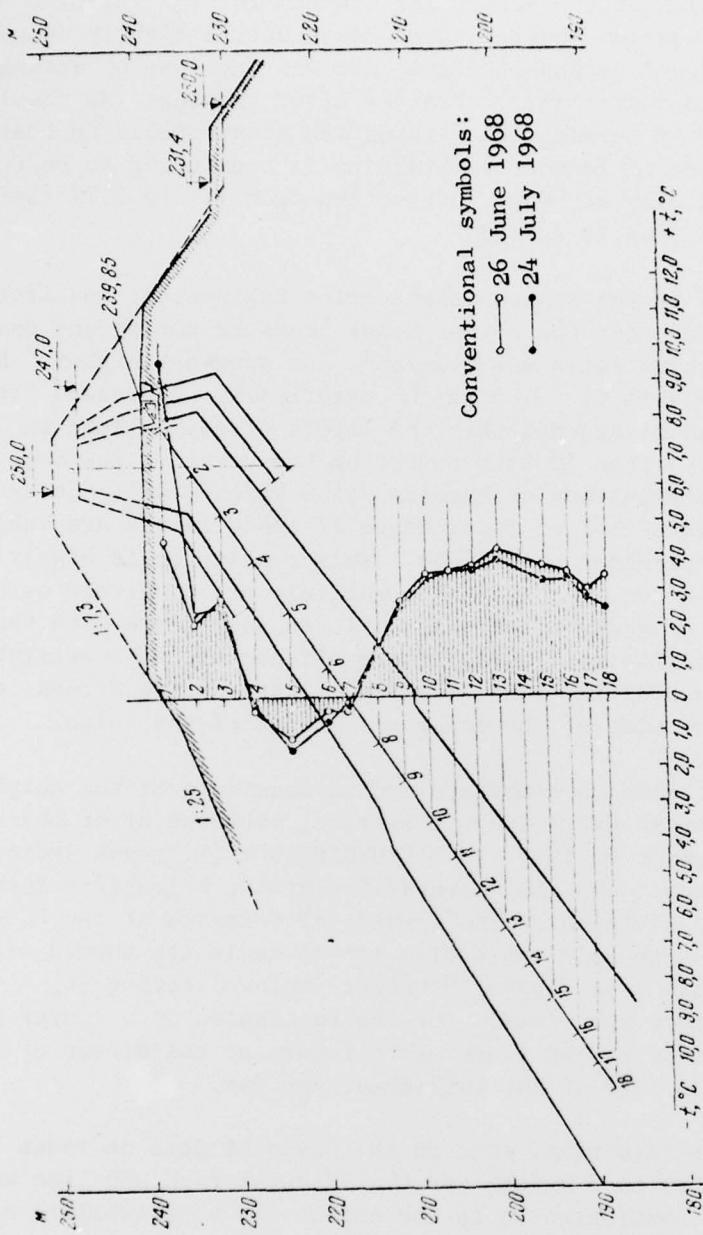


Figure 2. Temperature distribution over the height of the loam screen of the dam for the Vilyuysk Hydroelectric Station (summer 1968 - the second year of operation of the dam).

Once again let us emphasize the seriousness and complexity of the problem of research in cryogenic processes and phenomena in the soils of hydraulic engineering structures, and the need for detailed study of that problem.

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